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Dynamic Simulation of Dual-Speed Wind Turbine Generation

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Dynamic Simulation of Dual-Speed Wind Turbine Generation

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Abstract

Induction generators have been used since the early development of utility-scale wind turbine generation. An induction generator is the generator of choice because of its ruggedness, and low cost. With an induction generator, the operating speed of the wind turbine is limited to a narrow range (almost constant speed). Dual-speed operation can be accomplished by using an induction generator with two different sets of winding configurations or by using two induction generators with two different rated speeds.

With single-speed operation, the wind turbine operates at different power coefficients (Cp) as the wind speed varies. The operation at maximum Cp can occur only at a single wind speed. However, if the wind speed varies across a wider range, the operating Cp will vary significantly. Dual-speed operation has the advantage of enabling the wind turbine to operate at near maximum Cp over a wider range of wind-speeds. Thus, annual energy production can be increased. The dual-speed mode may generate less energy than a variable-speed mode; nevertheless, it offers an alternative to capture more energy than single-speed operation.

In this paper, dual-speed operation of a wind turbine will be investigated. One type of control algorithm for dual-speed operation is proposed. Results from a dynamic simulation will be presented to show how the control algorithm works and how power, current, and torque of the system vary as the wind turbine is exposed to varying wind speeds.

I. Introduction

The utility size wind turbine has been developed for many years [1]. The reliability of wind turbine generator has improved very dramatically. More attention is directed to improve energy capture, load alleviation, and other characteristics that will bring the cost of energy down. Many avenues have been explored and considered such as the development of variable-speed wind turbines [2-5] and some variable-speed systems use direct drives to eliminate the operation, maintenance, and the losses of the gearbox even in small scale applications [6-8]. However, the wind industry is very cautious when it comes to the cost of energy ($/kWh). Any technical advantage is balanced by the investment and operation and maintenance costs that accompany the technology. One of the concepts developed to increase energy capture is to employ dual-speed wind turbine generators. The dual-speed system can be implemented by using a dual winding induction generator with two different number of poles [9] or by using two separate induction generators. The wind turbine under consideration is assumed to be connected to two separate induction generators, which in this analysis, have synchronous speeds of 1200 rpm and 1800 rpm.

The system under consideration is shown in Figure 1. The wind turbine is connected to two induction generators via a gearbox. The smaller generator (generator 1) has a slower synchronous speed and the larger generator

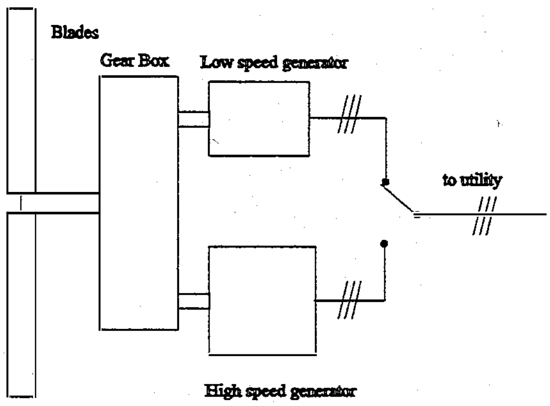

Figure 1. The physical diagram of a dual-speed wind turbine generation

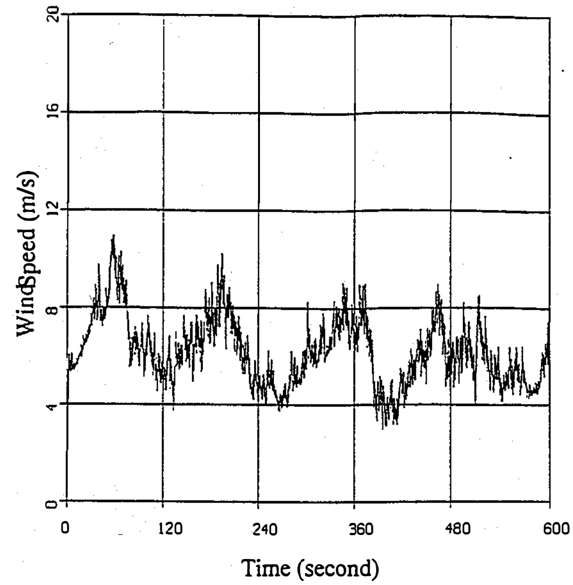

Figure 2. Wind speed applied to the wind turbine; wind speed average = 6 m/s

(generator 2) has a higher synchronous speed. The dual-speed operation of a wind turbine generation has the advantage of generating more energy compared to single-speed operation [10]. In Figure 2 the wind speed profile applied to the wind turbine is shown. The wind speed averages 6 m/sec with rough turbulence included. The organization of this paper is arranged as follows: Section II is used to explain the wind turbine aerodynamic characteristics. A simple comparison between single-speed and dual-speed is also presented in section II to illustrate the aerodynamic benefit of using two speed systems. In section III, the induction generator characteristics are discussed and in section IV the analysis of the simulation is given. Finally, the conclusion is presented in section V.

II. Wind Turbine Aerodynamic Characteristics

The wind turbine is normally characterized by its power coefficient versus its tip-speed ratio (C_p-TSR) curve, here the TSR is the tip-speed ratio, the ratio of the linear speed of the blade tip to the wind speed. A typical C_p-TSR curve is given in Figure 3. As shown in equation 1, it is desirable that the wind turbine is operated at high C_p values most of the time to capture more energy from wind. Given any size of a wind turbine, to operate the wind turbine at peak Cp all the time, the wind turbine should be operated in variable-speed with no electrical or mechanical design constraints. Dual-speed operation may generate less energy than variable-speed operation, however, in some wind turbine applications the dual-speed operation is a viable option in terms of energy captured, initial investment, and O&M cost.

In a fixed-frequency application, typical of larger wind farm turbines, the rotor speed of the generator is fixed, while the speed of the wind may vary across a wide range. Thus, the tip-speed ratio may vary across a wide range. The power captured by the wind turbine rotor may be written as shown in equation 1. From the equation 2, it is apparent that the power production from the wind turbine can be maximized if the system is operated close to $C_{p\text{-}max}$. Thus, it is necessary to keep the rotor speed in the vicinity of TSR_{Target}. Note that the

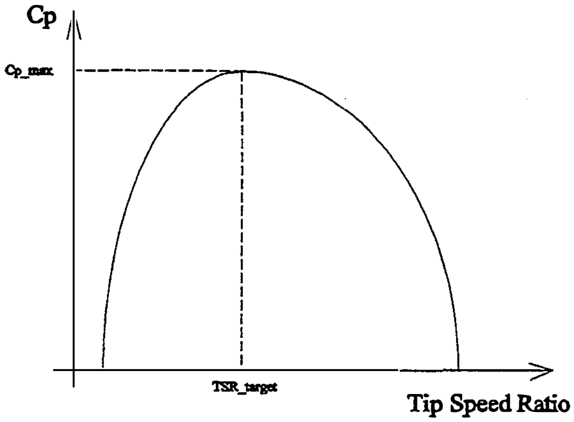

Figure 3. Typical Cp-TSR characteristic of a wind turbine

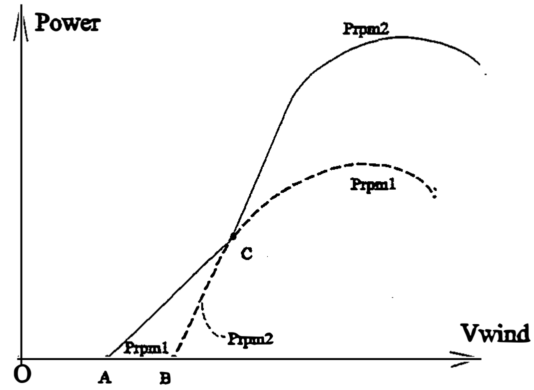

Figure 4. Power vs wind speed for a dual-speed wind turbine operation

$$P_{mech} = 0.5 * \rho * A * C_p * V^3 \tag{1}$$

where :

ρ = *air density* kg/m^3
A = *swept area* m^2
C_p = *coefficient of wind turbine*
V = *wind velocity* $m/\sec$

$$TSR = \frac{\omega_m R}{V} \tag{2}$$

where :

ω_m = *rotor speed in* $rad/\sec$
R = *radius of the blade in* m

tip-speed ratio is computed based on the ratio between the tip speed of the blade and the wind speed as shown in equation 2. As the wind speed changes, the rotor speed should be adjusted to maintain a constant tip-speed ratio. Unfortunately, the normal operating slip of an induction generator is very small and the rotor speed is practically constant. For a single-speed wind turbine, the operating TSR always changes as the wind speed varies. Thus if the wind speed varies across a very wide range, the operating TSR will vary across a very large range, and Cp deviates in a wider range from C_{pmax}. The operation of the wind turbine can only be optimized within a limited range of TSR. Using a dual-speed wind turbine, the operating TSR can be limited to a narrower range, thus the Cp does not vary too far from the C_{pmax}.

Figure 4 shows the steady-state prediction of the power output of the generator as a function of the wind speed. It is shown that if the wind turbine is operated only with one speed (generator 2), the operating point follows the path B, C, and Prpm2. With an additional smaller and slower generator, the path of the operating point can be extended to A, C, and Prpm2. Thus, when the wind speed is low, only generator 1 will be turned on. As the wind speed increases, the operating point moves from A to C. At point C, generator 2 is turned on and generator 1 is turned off. The gain in power generated by the wind turbine is represented by the triangle ABC.

III. Induction Generator

The equivalent circuit of an induction generator can be shown in Figure 5. It can be applied for a general induction machine including a wound rotor induction generator. For a squirrel cage, the Vr′ shown in the equivalent circuit is set to zero (short circuit rotor winding). In Figure 6, the torque speed characteristics of the

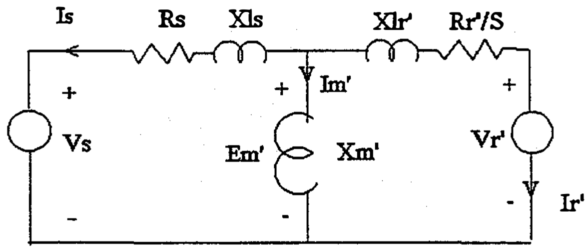

Figure 5. Equivalent circuit of an induction generator

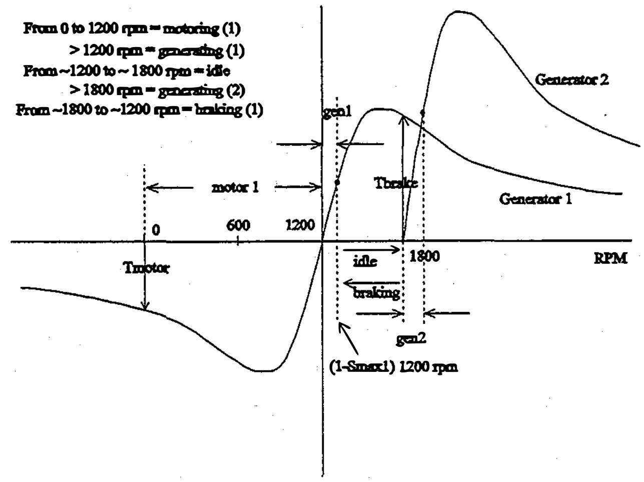

Figure 6. Torque-speed characteristics for different modes of operation

two generators are shown. The wind turbine is started by motoring generator 1, as the wind speed increases,therotor rpm passes the synchronous rpm of generator 1and it starts generating. As the wind speed increases, generator 1 reaches its rated power, thus the operation must be transferred to generator 2. If the wind speed decreases, the generating unit will be transferred back to generator 1.

The generators' characteristics depend on the parameter of the induction generators. Torque and power change as the rotor speed varies. The wind turbine is connected to two induction generators, which, in this analysis, have synchronous speeds of 1200 rpm and 1800 rpm. The synchronous speeds cannot be chosen arbitrarily, because the number of poles of an induction machine is an even number and the frequency of supply is a constant 60 Hz. The power rating of the two induction generators are chosen differently; however, the stator voltage must be the same. For example, the slower induction generator can have a rated power that is lower than the faster induction generator. We may also consider the fact that for a wind turbine operating in a constant power coefficient Cp, the power is proportional to the cube of the speed.

An induction generator has an operating speed that is higher than the synchronous speed, and thus the slip is always negative. Operating at a higher slip, the generator has low efficiency (higher losses) thus increasing the temperature of the winding, which will lead to insulation failure. The approximate slip at which the peak torque occurs can be computed as follows:

$$S_{peak} = \frac{R_r'}{\sqrt{R_s^2 + (X_{lr}' + X_{ls})^2}} \tag{3}$$

Thus, the slope of the torque characteristic is affected by the rotor resistance Rr′ and other parameters. A smaller rotor resistance makes the slope of the torque-speed steeper.

Dual-Speed Operation (DS):

The operation of a wind turbine at two different rotor speeds is described in Figure 6. The system can be started by operating the induction machine (generator 1) as a motor at a lower rpm to start the wind turbine. As the rotor speed reaches the (lower) synchronous speed, the wind turbine starts generating. As the wind speed increases, it continues to generate until another set point is reached. At Pchosen, generation must be switched from generator 1 to generator 2.

In practice the implementation can be accomplished in several different ways. One option is to use the rpm as the set point. From Figure 4, the wind turbine is operated by using generator 1 when the wind speed is low. As the wind speed increases, the power generated by generator 1 also increases until it reaches point C. After point C it is obvious that generator 2 will produce more power than if the wind turbine is connected to generator 1. Considering that both generator 1 and generator 2 are induction generators operated at constant frequency, the rotor speeds rpm1 and rpm2 actually vary with slip. As the power increases, the slip also increases. Thus it is convenient to use the rotor speed to signal the change of state from generator 1 to generator 2 or vice versa. A simple logic controller can be developed to change the status from one to another. It is necessary to know the parameter of the generator to compute the exact rpm at which to change the status. This data can be obtained from the generator manufacturer or a simple test can be conducted in the lab. The most important thing is to determine the rpm of generator 1 at power = Pchosen. Possible logic to be used in this algorithm is given below:

```
if ( (rpm < rpmsyn1 ) .and. (vwind < vstartgen)) then ................................ (a)
  shutdown
else if(( rpm < rpmsyn1 x Smax1) .and. (vwind > vstartgen) ) then ...................... (b)
  generator 1
else if( ( rpm  > rpmsyn1 x Smax1 ) .and. (rpm < rpmsyn2) ) then ....................... (c)
  idle condition, start counting idle_time
else if ( rpm > rpmsyn2 ) then ......................................................... (d)
  generator 2
  if(generator2 and power < pgen2lowlim) then
     switch_to_generator1
  end if
else if ( idle_time > t_wait ) then .................................................... (e)
  generator 1
end if
```

where

rpmsyn1	=	synchronous rpm for generator 1
rpmsyn2	=	synchronous rpm for generator 2
generator 1	=	only generator 1 is on
generator 2	=	only generator 2 is on
idle condition	=	neither generator 1 nor generator 2 is on (start counting)
t_wait	=	predetermine time, if the system is idle for more than this preset time, it is concluded that the wind velocity is too weak to bring the wind turbine above rpmsyn2
shutdown	=	neither generator 1 nor generator 2 is on
Smax1	=	slip (negative value) at which the wind turbine is disconnected from generator 1 to go to idle condition
vwind	=	wind speed (after low pass filter)
vstartgen	=	precomputed wind speed value above which the wind turbine should be operated
induction machine	=	electric machine used regardless of the mode of operation. Thus induction machine 1 can be operated as generator 1 (during generation) or motor 1 (during startup).
pgen2lowlim	=	lower limit of power to operate in gen. 2 before transfering back to gen. 1
pchosen	=	upper limit of power generated by gen 1 before transfering to gen. 2

Alternative logic can be used to replace slip Smax1 and rpm by power measurements in logic (b) and (c) above:

rpm	in logic (b) and (c) can be replaced by power
rpmsyn1 x Smax1	in logic (b) and (c) can be replaced by Pchosen

IV. Analysis of the Simulation

The system is simulated with a wind turbine connected to two different generators. It is assumed that the generators were both connected to the wind turbine all the time so that the inertia of the generators are lumped together and the inertia does not change during the transition from generator 1 to generator 2 and vice versa. At any time, only one of the generators can be electrically connected to the grid. The generators are mechanically connected to the wind turbine via a gearbox. The stiffness and the damping of the mechanical equations are given as an input to the program.

Condition of Simulation: Wind Speed Average (6 ± 3) m/s

The wind speed (as shown in Figure 2) is derived from a computed wind speed with turbulence. The data is updated every half second. The wind speed is filtered by a low pass filter and the filtered wind data is used as an observer. The filtered wind speed is given as a condition to the system (as a signal to decide the control decision to respond to the wind speed input). The wind speed information will be used to signal the controller to turn on the generator and generate electricity.

The rotor speed is used as a feedback. Using the rotor speed and wind speed, the program computes the instantaneous aerodynamic power and torque. The aerodynamic torque and the generator torque determine the speed of the wind turbine. Figure 2 shows a typical wind speed used in the simulation.

Wind speed and rotor speed

At low wind speed the system waits until the wind speed goes above the starting point (VSTARTGEN). As the wind speed reaches the starting point, the induction machine 1 starts as a motor to bring the rotor speed to above 1200 rpm. The rpm of the rotor increases (as shown in Figure 7) from motoring (below 1200 rpm) to generating (above 1200 rpm). As the wind speed increases, the power increases as the slip increases. The slip corresponds indirectly to the power generated by generator 1. As the slip reaches Smax1, generator 1 is electrically disconnected from the wind turbine.

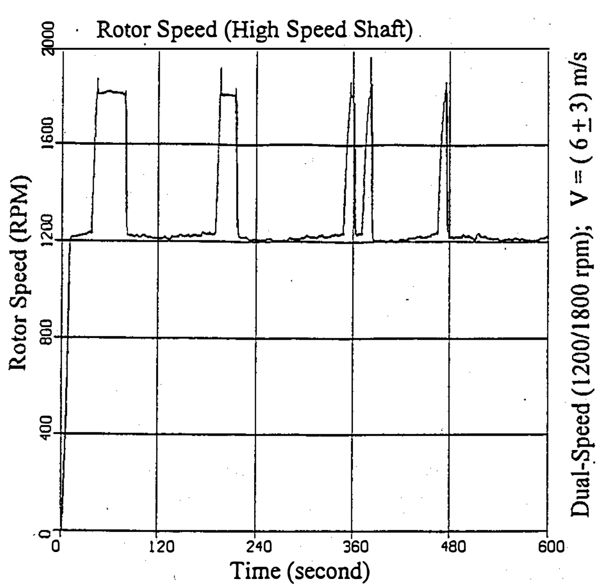

Figure 7. RPM variation as the wind speed changes

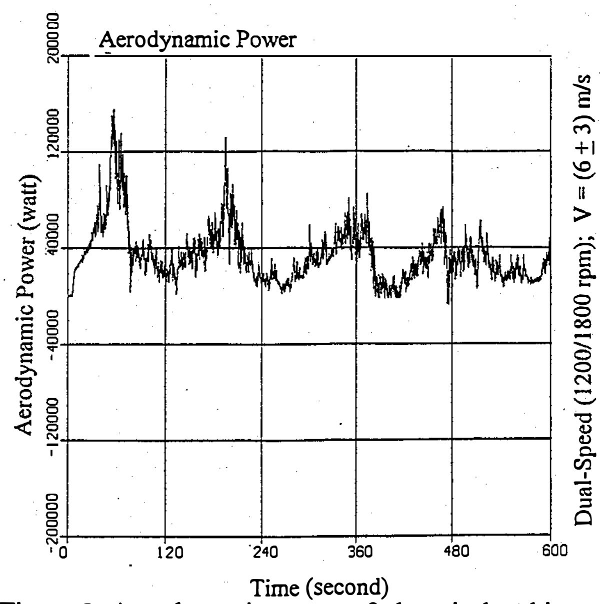

Figure 8. Aerodynamic power of the wind turbine

There is an idle time between the time generator 1 disconnected from the utility to the time generator 2 is connected to the utility. If the wind speed is strong enough, during the idle time, the rotor speed will be brought to 1800 rpm. Thus, during the transition from 1200 rpm to 1800 rpm, both generators are idle. From the condition given by the wind speed input, the rotor speed increases to 1800 rpm several times. The wind turbine is now operating only with generator 2 connected to it. As the wind speed decreases, the power generated by generator 2 and the slip also decrease. When generator 2 generates below its lower limit, generator 2 is disconnected and generator 1 is reconnected (braking condition). From Figure 7 it can be seen how the generator changes from generator 1 to generator 2 based on the wind condition. The corresponding aerodynamic power is shown in Figure 8. It is shown that the aerodynamic power can follow the wind speed.

Stator current and torque:

The stator current of generator 1 (Ias1) and the typical starting torque are shown in Figure 9 and 10 respectively. The starting current of generator 1 as shown in Figure 9 has about the same magnitude as the braking current (to ramp down from rpm2 to rpm1). The braking times are shorter than the start-up time. The length of time during the start up and the braking is affected by the wind speed. The wind turbine is driven by the wind speed during the start up and during the braking the generator opposes the wind speed. Note that during startup, the power comes from the utility while during braking, the power goes into the utility.

From Figure 10, the operation of the induction machine 1 is started as a motor to start the wind turbine from zero rotor speed to 1200 rpm. The torque ripple shown in Figure 10 is also affected by the damping and the stiffness of the mechanical characteristic of the wind turbine. It is shown in Figure 9 and Figure 10 that there is a large starting torque transient and stator current (in general it can be as high as 800% of the rated stator current). It is shown that the stator current Ias1 decreases as the speed close to the 1200 rpm (operation at low slip). Similarly, in generating mode, the slip of generator 1 is a small negative value, thus the stator current is within normal operating region. As generator 1 produces more power, the slip increases and the stator current also increases, until the slip-limit (smax1) or the power limit is reached before the operation is transferred to generator 2. Another advantage of using smaller generator (induction machine) to start the wind turbine is the fact that in general the smaller induction machine has a higher value of leakage inductances and resistances on the stator and rotor winding. Therefore, a smaller induction machine has lower starting current than a larger one.

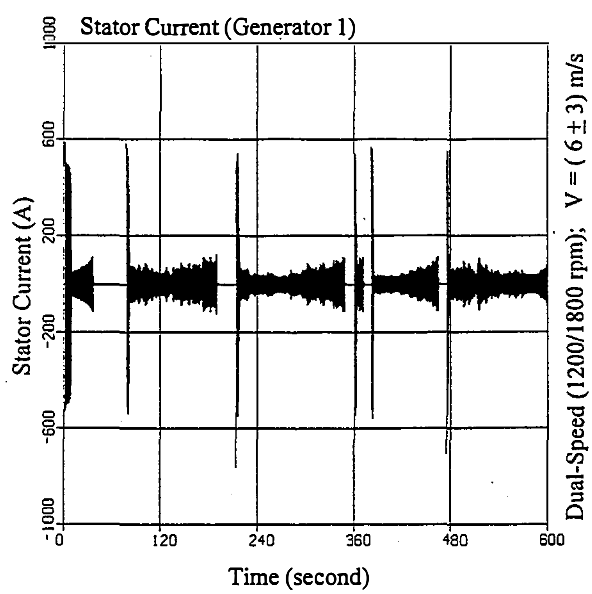

Figure 9. Stator current variation as the wind speed changes

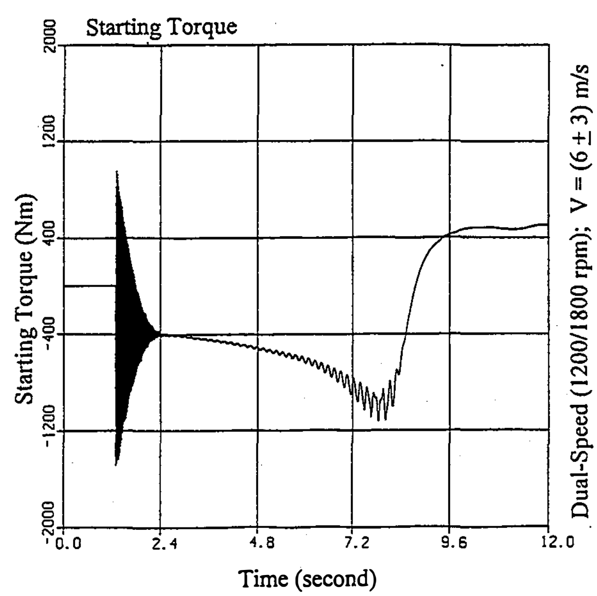

Figure 10. Starting torque of the wind turbine

Electrical Energy:

The energy generated by the generators is shown in Figure 11 and Figure 12. As shown in Figure 11, the starting of the wind turbine takes electrical energy from the utility thus contributing to negative energy. It is shown that during the idle condition, there is no additional energy for generator 1 and generator 2. In Figure 12, the energy generated by generator 2 is shown. With this lower wind speed, the contribution from generator 2 to the total energy is not very significant. However, in the higher wind speed, generator 2 contributes more energy than the lower speed generator (generator 1). Note that if the wind turbine has only generator 2, the operation in low wind speed region will lead to light load operation, thus efficiency is not optimum (low power factor, higher iron loss, etc.). On the other hand, with dual-speed operation, the wind turbine will use generator 1 in the lower wind speed, thus efficiency will be improved in this region.

At lower wind speeds, if the wind is not high enough to generate electricity, the generator can be operated in coasting mode to allow a faster return to normal operation in case there is an increase in the wind speed. At higher wind speeds, generator 2 will operate a higher power. In general, the wind turbine will operate in the stall mode when the wind speed increases more.

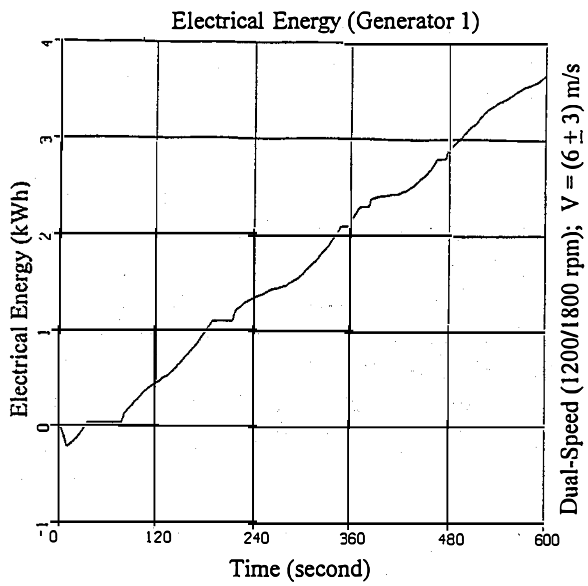

Figure 11. Electrical energy of generator 1

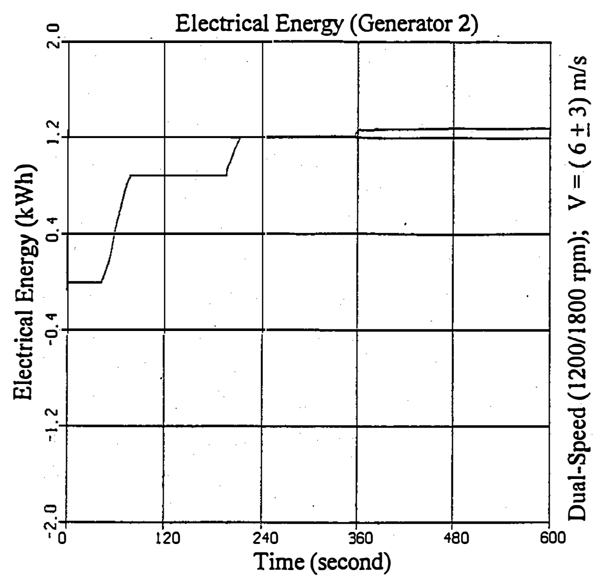

Figure 12. Electrical energy of generator 2

V. Conclusion

Compared to single-speed operation, dual-speed operation increases energy production. The gain in energy is achieved mainly in the lower wind speed region at which single-speed operation has limited rpm operation. With dual-speed operation, the wind turbine are operated at higher efficiency (higher Cp average). Dual-speed operation allows a more efficient operation of the induction generator by operating each generator close to its rated operating power. Thus the larger generator does not have to operate at light load (low power factor, low efficiency) during low wind speed. The smaller generator is used to start up the wind turbine, thus it requires a lower inrush current during the start up. Dual-speed operation is a mature technology with a low cost of operation and maintenance. Presently, dual-speed operation has a lower cost of initial investment than a variable-speed wind turbine.

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Appendix

The parameters of the induction generators and wind turbine are given below:

Input parameters are given in 60 Hz

Induction motor paramters:

Stator Winding : **Rotor winding (referred to the stator):**

Generator 1: (poles = 6)

$Rs1 := 0.085$ ohm

$Xls1 := 0.382 \cdot$ohm

$Rr1' := 0.1228 \cdot$ohm

$Xlr1' := 0.382 \cdot$ohm

Magnetizing winding :

$Xm1 := 13.08 \cdot$ohm

Generator 2: (poles = 4)

$Rs2 := 0.0185 \cdot$ohm

$Xls2 := 0.102 \cdot$ohm

$Rr2' := 0.017 \cdot$ohm

$Xlr2' := 0.102 \cdot$ohm

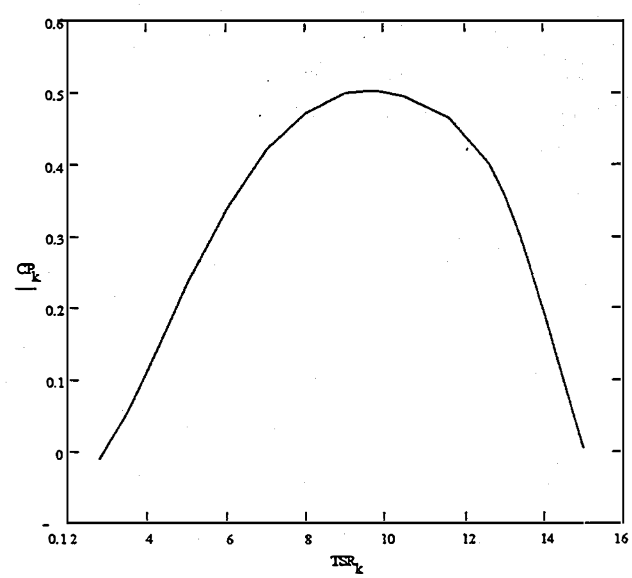
Magnetizing winding :

$Xm2 := 3.325 \cdot$ohm

$$Vrated := \frac{480}{\sqrt{3}} \cdot \text{volt}$$

The wind turbine parameter:

Blade diameter = 26 m
Rated power = 285 kW
Highest rpm = 57 rpm (low speed shaft)



Cp_TSR of the wind turbine